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SEISMIC EFFECTIVENESS OF TUNED MASS DAMPERS CONSIDERING SOIL–STRUCTURE INTERACTION

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SUMMARY

This paper presents how soil–structure interaction affects the seismic performance of Tuned Mass Dampers (TMD) when installed on flexibly based structures. Previous studies on this subject have led to inconsistent conclusions since the soil and structure models employed considerably differ from each other. A generic frequency-independent model is used in this paper to represent a general soil–structure system, whose parameters cover a wide spectrum of soil and structural characteristics. The model structure is subjected to a stationary random excitation and the root-mean-square responses of engineering interest are used to measure the TMD's performance. Extensive parametric studies have shown that strong soil–structure interaction significantly defeats the seismic effectiveness of TMD systems. As the soil shear wave velocity decreases, TMD systems become less effective in reducing the maximum response of structures. For a structure resting on soft soil, the TMD system can hardly reduce the structural seismic response due to the high damping characteristics of soil–structure systems. The model structure is further subjected to the NS component of the 1940 El Centro, California earthquake to confirm the TMD's performance in a more realistic environment. Copyright © 1999 John Wiley & Sons Ltd.

KEY WORDS: Tuned Mass Damper (TMD); structural control; soil–structure interaction; root-mean-square response

INTRODUCTION

Significant progress has been made in the field of structural control during the past two decades. Two books[1,2] have been published to summarize the recent developments of active control and passive devices. In most of the research work, structures are assumed to be fixed at base and the effect of soil–structure interaction on the performance of control systems is neglected. In practice, however, many structures are built on soft soil and strong interaction appears between soil and the superstructure. On the one hand, Wolf[3,4] and Luco and Wong[5] have shown that strong soil–structure interaction significantly modifies the dynamic characteristics of structures such as frequencies, damping, mode shapes, etc. and adopts the seismic input to the superstructure due to the scattering effect of rigid foundation. On the other, applying an active structural control system or a passive device to a structure mainly changes the structure's dynamic characteristics.[6] The rational design of a control system thus depends on the understanding of the structures' dynamic

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characteristics which in turn are affected by soil–structure interaction. Therefore, it is reasonable to say that soil–structure interaction will generally affect the performance of a control system or device. Without taking this factor into account, a control system might be installed when it is considered unnecessary due to overestimation of the responses of uncontrolled structures or a control system may not perform optimally due to erroneous identification of structural properties.

Xu and Kwok[7] studied the effect of soil–structure interaction on the performance of Tuned Mass Dampers (TMD) for wind applications. They examined a 76-storey concrete building and a 370 m TV tower with a tapering circular cross-section from 20 to 10 m in diameter. Both structures are supported on shallow rigid footings embedded in soil. They concluded that when soil is very soft, tuned mass dampers cannot effectively reduce the response of the soil–structure system; and when soil is moderately stiff, the dampers should be tuned into the fundamental frequency of the soil–structure system instead of the fixed-base structure in order to optimize the dampers' performance. Samali *et al.*[8] have drawn similar conclusions on the TMD's seismic performance for soil-structure systems.

However, recent studies by Gao *et al.*[9] on the TMD's seismic performance led to a different conclusion. In their recent studies they used a five-storey idealized building that is supported by a rigid rectangular footing either resting on or embedded in soil. Tuned mass dampers were shown to be as effective to mitigate the seismic responses of a soil–structure system as fixed-base structures provided that the fundamental frequency of the soil–structure system is accurately estimated for the tuning of the dampers. This conclusion is inconsistent with that drawn from the previous studies. They claimed that the results from the earlier studies are correct only for special cases and cannot be generalized.

In the studies by Gao *et al.*[9] mentioned above, soil is modeled as an elastic half-space without material damping. This assumption may be acceptable for wind loading problems, but becomes questionable for seismic applications. In addition, the dynamic characteristics of the example structure is not sensitive to soil–structure interaction. For instance, the fundamental frequency of the soil–structure system is reduced only by 5 per cent when the soil shear wave velocity decreases from ∞ to 150 m/s. Using such a structure to investigate the effect of soil–structure interaction on the TMD's performance would lead to incorrect conclusions.

The objective of the present study is to better understand the effect of soil–structure interaction on the TMD's performance. The goal is achieved by performing extensive parametric studies on a shear-type of building structure. Inconsistent conclusions drawn from previous studies can thus be eliminated. In this paper, a square shear building with a rigid concrete mat footing is considered. It rests on an infinite soil medium which is modeled as a viscoelastic half-space. The tuned mass damper is installed on the top floor of the structure. The soil's shear wave velocity varies from 100 m/s to ∞ (rigid base). For certain structural and foundation dimensions, the performance of TMD system under different soil conditions is studied.

MODELING OF SOIL–STRUCTURE–TMD SYSTEMS

Equation of motion

The soil–structure–TMD system under consideration consists of a viscously damped, linear elastic, shear-type of building structure, a tuned mass damper, a rigid mat footing and a half-space

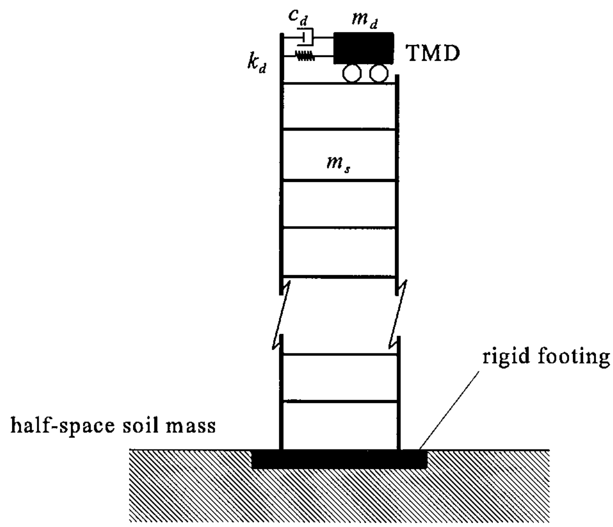

Figure 1. Soil–structure–TMD system

soil mass. It is shown schematically in Figure 1. For simplicity, this paper focuses on two-dimensional analysis.

Fixed-base structure–TMD systems

When supported on very stiff soil mass, the structure and TMD system can be considered to be a fixed base. The equation of motion of the superstructure without tuned mass dampers subjected to seismic excitations can be written as

$$M_s \ddot{X}_s + C_s \dot{X}_s + K_s X_s = -M_s E_s \ddot{x}_g \tag{1}$$

in which M_s, C_s and K_s are the mass, damping and stiffness matrices of the superstructure, respectively, X_s, $\dot{X}_s$ and $\ddot{X}_s$ are the relative displacement, velocity and acceleration vectors of the structure with respect to base; E_s is a location vector which defines the location of effective seismic loads; and $\ddot{x}_g$ is the horizontal ground acceleration. When a tuned mass damper is installed atop the structure, the equation of motion of the structure–TMD system becomes

$$\begin{bmatrix} M_s & 0 \\ 0 & m_d \end{bmatrix} \begin{Bmatrix} \ddot{X}_s \\ \ddot{x}_d \end{Bmatrix} + \begin{bmatrix} C_s + c_d \Gamma_1 \Gamma_1^T & -c_d \Gamma_1 \\ -c_d \Gamma_1^T & c_d \end{bmatrix} \begin{Bmatrix} \dot{X}_s \\ \dot{x}_d \end{Bmatrix} + \begin{bmatrix} K_s + k_d \Gamma_1 \Gamma_1^T & -k_d \Gamma_1 \\ -k_d \Gamma_1^T & k_d \end{bmatrix} \begin{Bmatrix} X_s \\ x_d \end{Bmatrix} = -\begin{Bmatrix} M_s E_s \\ m_d \end{Bmatrix} \ddot{x}_g \tag{2}$$

in which m_d, c_d and k_d denote the mass, damping and stiffness of the damper, x_d is the relative displacement of the damper with respect to the base, Γ_1 is a location vector which defines the location of the damper.

Flexible-base structure–TMD systems

When the structure is supported on soft soil, soil–structure interaction could strongly affect the dynamic response of the structure. Soil–structure interaction usually can be regarded as the

superposition of two components: kinematic and inertial. For structure resting on shallow rigid footings, inertial interaction is dominant and can be characterized by impedance functions of a rigid foundation.

Numerous research work has shown that the impedance functions of a rigid footing on half-space soil medium are functions of the frequency of external excitation, the shape of the footing, the Poisson's ratio of the soil and other parameters. Based on the analytical and experimental results collected, Dobry and Gazetas[10] suggested a simple approach of calculating the impedance functions of shallow rigid footings on half-space medium. They expressed the impedance functions as $K + i\omega C$, where ω is the angular frequency of the excitation, and presented the effective stiffness K and effective damping C in a graphical format.

For a square rigid footing resting on soil medium without material damping, the effective stiffness for translational and rocking modes are, respectively, expressed as

$$K_x = k_x \frac{9LG}{2 - v} \quad \text{and} \quad K_{ry} = k_{ry} \frac{3{\cdot}2G}{1 - v} I_y^{0{\cdot}75} \tag{3}$$

where L and I_y denote the half-width and the moment of inertia of the footing, and G and v are the shear module and the Poisson's ratio of the soil material. The dimensionless coefficients k can be obtained from Figure 2.

Due to soil–structure interaction, part of the vibrational energy in the structure is transferred through the foundation into the unbounded soil medium. This effect is often referred to as radiation damping, which can be expressed as

$$C_x = c_x \rho_s V_s A \quad \text{and} \quad C_{ry} = c_{ry} \rho_s \frac{3{\cdot}4 V_s}{\pi(1 - v)} A \tag{4}$$

for the translational and rocking modes, respectively. In equation (4), A is the foundation area and ρ_s and V_s, respectively, denote the mass density and shear wave velocity of the soil. The dimensionless damping coefficients c are also shown in Figure 2.

If the material damping of soil medium, represented by damping ratio β, is included, the effective stiffness and damping coefficients can be determined by[10]

$$K(\beta) = K - \omega C \beta \quad \text{and} \quad C(\beta) = C + \frac{2K}{\omega} \beta \tag{5}$$

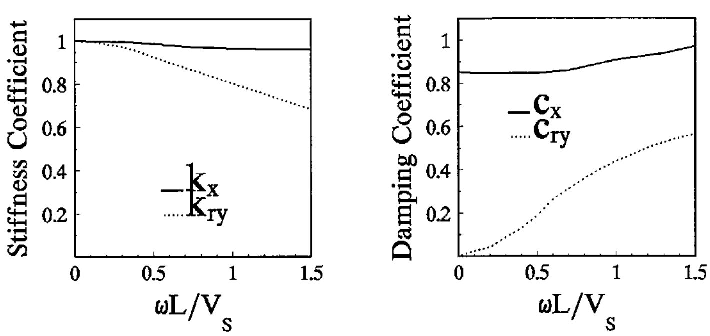

Figure 2. Dimensionless stiffness and damping coefficients of shallow rigid footing on half-space soil (Taken from Reference 10)

The stiffness and damping coefficients calculated from equation (5) are frequency-dependent. For high-frequency vibration, the radiation damping C may outweigh the material damping. For low frequency, $C(\beta)$ is usually dominated by the soil material damping.

Previous studies[11] on soil–structure interaction under earthquake loading have shown that the inertial interaction between soil and structure of shallow foundations can be modeled by a set of frequency-independent springs and dashpots. Their stiffness and damping coefficients, designated by K_F and C_F, are equal to $K(\beta)$ and $C(\beta)$ evaluated at the fundamental frequency of the soil–structure system. The motion equation of the soil–structure–TMD system can be written as

$$\begin{bmatrix} M & 0 \\ 0 & M_F \end{bmatrix} \begin{Bmatrix} \ddot{X} \\ \ddot{X}_F \end{Bmatrix} + \begin{bmatrix} C & -C\Gamma \\ -\Gamma^T C & \Gamma^T C \Gamma + C_F \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{X}_F \end{Bmatrix} + \begin{bmatrix} K & -K\Gamma \\ -\Gamma^T K & \Gamma^T K \Gamma + K_F \end{bmatrix} \begin{Bmatrix} X \\ X_F \end{Bmatrix} = -\begin{bmatrix} M & 0 \\ 0 & M_F \end{bmatrix} \begin{bmatrix} \Gamma \\ I \end{bmatrix} \begin{Bmatrix} \ddot{x}_g \\ \ddot{\theta}_g \end{Bmatrix} \quad (6)$$

in which M, C and K correspond to the structural properties in equation (1) or the structure–TMD properties in equation (2), depending on whether the TMD is present or not; X is the corresponding structural/structure–TMD displacement vector relative to the free field ground motion; X_F is the displacement vector of the rigid footing relative to the free field ground motion; M_F is the mass matrix of the rigid footing; Γ is a transformation matrix which defines the transformation from the free field motion to that of the superstructure. The quantities $\ddot{x}_g$ and $\ddot{\theta}_g$ are the translational and rocking components of the free field acceleration, and $\ddot{\theta}_g$ is assumed to be zero in this study.

Here it is noted that, although the structure alone can be considered as a classically damped system, the combined system of the structure and soil medium is usually not. Therefore, the full-matrix analysis instead of the decoupled modal analysis is used for the calculation of structural responses. This non-proportional damping property could significantly affect the TMD's performance as can be inferred from the study by Igusa and Kiureghian.[12]

Parameters of an example soil–structure–TMD system

A 12-storey shear building resting on viscoelastic soil medium as sketched in Figure 1 is considered as an illustrative example. The mat footing of 16 m × 16 m in square is assumed rigid. To study the effect of soil–structure interaction on the performance of TMD system under various circumstances, the damping ratio of all modes of the superstructure alone is assumed to be $\xi = 1$, 2, 3 or 5 per cent. The tuned mass damper atop the structure is of 8 per cent damping ratio and mass equal to 1 per cent of the total mass of the superstructure. To model various soil conditions, five shear wave velocities are considered. They range from 100 m/s to infinity.

All parameters of the soil–structure–TMD system are summarized in Table I. To understand how strong the soil–structure interaction is, the fundamental frequency and the equivalent damping ratio of the first mode of the soil-structure system without dampers are determined for five soil conditions and listed in Table II. As one can see, the fundamental frequency is reduced by 45 per cent when the shear wave velocity of the soil medium varies from ∞ to 100 m/s. On the contrary, the damping ratio increases significantly as the soil medium becomes softer. When the soil becomes very soft ($V_s = 100$ m/s), the damping ratios corresponding to different ξ values are of little difference because the material and radiation damping of the soil is dominant in this case.

Table I. The parameters of the soil–structure–TMD system

Height H		TMD mass m_d		Floor mass m_s		Floor mass moment of inertia I_s		Interval stiffness
(a) *Superstructure–TMD*								
45 m (12 storeys)		$6{\cdot}4 \times 10^4$ kg		$5{\cdot}3 \times 10^5$ kg		0		$8{\cdot}4 \times 10^8$ N/m
(b) *Rigid footing*								
	Size			Mass			Mass moment of inertia	
	16 m × 16 m			$9{\cdot}8 \times 10^5$ kg			$4{\cdot}9 \times 10^7$ kg m^2	
(c) *Soil mass*								
				Shear modules G (N/m^2)				
v	β	$V_s = 100$ m/s	$V_s = 150$ m/s		$V_s = 200$ m/s		$V_s = 350$ m/s	$V_s = \infty$
0·35	0·10	$1{\cdot}7 \times 10^7$	$4{\cdot}3 \times 10^7$		$8{\cdot}4 \times 10^7$		$2{\cdot}8 \times 10^8$	∞

Table II. Fundamental frequency and damping ratio of the soil–structure system

	V_s(m/s)	100	150	200	350	∞ (fixed-base)
	ω_1 (rad/s)	2·7	3·5	4·1	4·6	5·0
ξ_1 (%)	($\xi = 1\%$)	7·9	5·7	4·1	2·2	1·0
	($\xi = 2\%$)	8·0	6·1	4·6	3·0	2·0
	($\xi = 5\%$)	8·5	7·1	6·3	5·4	5·0

The significant change in both frequency and damping ratio indicates the presence of strong soil-structure interaction.

STOCHASTIC ANALYSIS

Stochastic input

Let $H_{x_j}(\omega)$ be a transfer function from the ground acceleration $\ddot{x}_g(t)$ to the displacement $x_j(t)$ at the jth floor of the structure, and consider $\ddot{x}_g(t)$ as a stationary stochastic process. The mean-square steady-state displacement can then be determined by

$$E[x_j^2] = \int_{-\infty}^{\infty} |H_{x_j}(\omega)|^2 S(\omega)\, \mathrm{d}\omega \tag{7}$$

in which $S(\omega)$ is the power spectral density function of seismic ground acceleration $\ddot{x}_g(t)$. In the following analysis, the modified Kanai–Tajimi spectrum is used:[13]

$$S(\omega) = \frac{1 + 4\xi_g^2\,(\omega^2/\omega_g^2)}{(1-(\omega^2/\omega_g^2))^2 + 4\xi_g^2\,(\omega^2/\omega_g^2)} \cdot \frac{S_0}{1+(\omega^2/\omega_h^2)} \tag{8}$$

Table III. Model parameters of seismic ground motions

Soil classification (shear wave velocity)	I ($V_s \leqslant 140$ m/s)	II (140 m/s $< V_s \leqslant 250$ m/s)	III (250 m/s $< V_s \leqslant 500$ m/s)	IV ($V_s > 500$ m/s)
ω_g (rad/s)	41·89	31·42	25·13	16·75
ξ_g	0·64	0·72	0·80	0·90
ω_h (rad/s)		25·13		

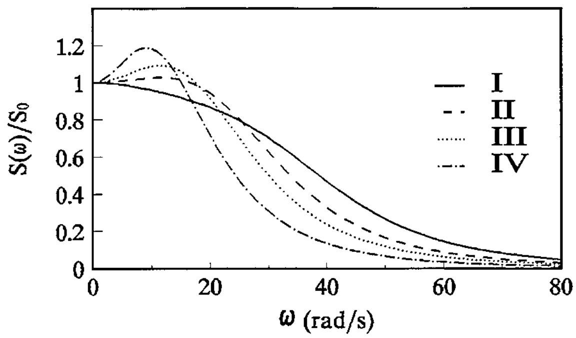

Figure 3. Power spectrum of ground acceleration

where ω_g, ξ_g and ω_h are given in Table III and S_0 represents the intensity of ground acceleration. The power spectrum density expressed by equation (8) is plotted in Figure 3 for various soil conditions.

Parametric analysis

The seismic performance of a damper can be measured by a normalized Root-Mean-Square (RMS) response

$$R_{x_j} = \sqrt{\frac{E[x_j^2]}{E[\bar{x}_j^2]}} \tag{9}$$

where $E[x_j^2]$ and $E[\bar{x}_j^2]$ are, respectively, the mean-square responses of the controlled and uncontrolled structure supported on soil medium. When $R_{x_j} < 1{\cdot}0$, the tuned mass damper can be used to mitigate the seismic response x_j. The smaller the value R_{x_j}, the more effectively the damper performs. In what follows, the relative displacement x_1 and the absolute acceleration $\ddot{y}_1$ at the top floor of the structure and the base shear force Q_b will be discussed at length. The translational (x_F) and rocking (θ_F) responses of the spread footing will also be reported.

TMD's performance for fixed-base structures

To study the effect of structural damping on the control performance of TMD system, the responses of a fixed-base controlled structure are calculated for different structural damping

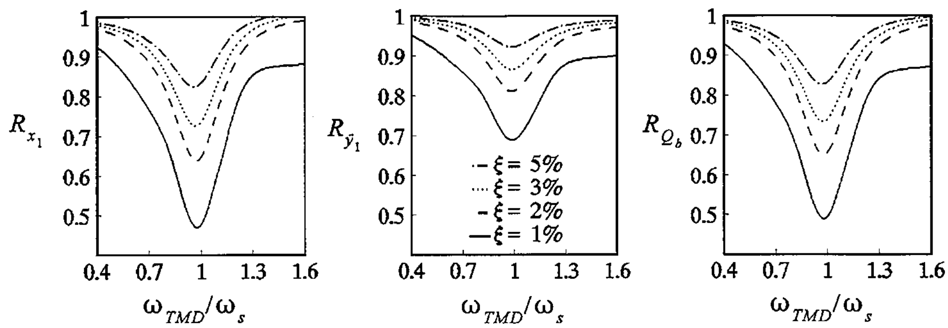

Figure 4. Responses of fixed-base structures

ratios. As a function of the frequency ratio $\omega_{\mathrm{TMD}}/\omega_{\mathrm{s}}$, the normalized RMS responses R_{x_1}, $R_{\ddot{y}_1}$ and R_{Q_b} are plotted in Figure 4 in which ω_{TMD} and ω_{s} are the frequency of the tuned mass damper and the fundamental frequency of the structure, respectively.

It can be seen from Figure 4 that the tuned mass damper is most effective around $\omega_{\mathrm{TMD}}/\omega_{\mathrm{s}} = 1$ as shown by previous researchers.[4] Among the three response quantities of engineering interest, the displacement and the base shear can be controlled by TMD more effectively than the absolute acceleration. This is because the absolute acceleration of the structure could be favorable to higher modes that a damper 'tuned into the fundamental mode of the structure' cannot regulate.

It can also be observed that the performance of the damper greatly degrades with the increasing structural damping. For 1 or 2 per cent damping, the RMS displacement and base shear can be reduced by 35–50 per cent and the RMS acceleration by 20–30 per cent. However, when the structural damping increases to 5 per cent, the reduction becomes 15 per cent for the RMS displacement and base shear and much less for the absolute acceleration.

TMD's performance for structures on soft soil

As mentioned in the Introduction, the seismic performance of TMD systems is expected to be appreciably affected by soil–structure interaction. To quantify this effect, the normalized RMS structural responses are calculated for various soil's shear wave velocities and plotted in Figure 5 and 6 for different structural dampings as a function of the frequency ratio $\omega_{\mathrm{TMD}}/\omega_i$. The quantity ω_i is the fundamental frequency of the soil–structure system. For a fixed-base structure, $\omega_i = \omega_{\mathrm{s}}$. From Figures 5 and 6 it can be seen that the damper also performs the best around $\omega_{\mathrm{TMD}}/\omega_i = 1$ for structures on soft soil. However, it can be clearly seen from Table II that the fundamental frequency of the soil-structure system ω_i is significantly lower than that of the structure alone. Therefore, a damper is much less effective to reduce the structural responses if tuned into ω_{s}.

For lightly damped structures as indicated in Figure 5, the tuned mass damper reaches its ultimate performance when the structure is resting on stiff soil, i.e. $V_{\mathrm{s}} = \infty$ and 350 m/s. The RMS displacement and base shear in these cases can be reduced by 30–50 per cent. With the softening of the soil medium, the normalized RMS responses increase and thus the damper's performance degrades. In particular, when V_{s} is smaller than 150 m/s, the RMS displacement and

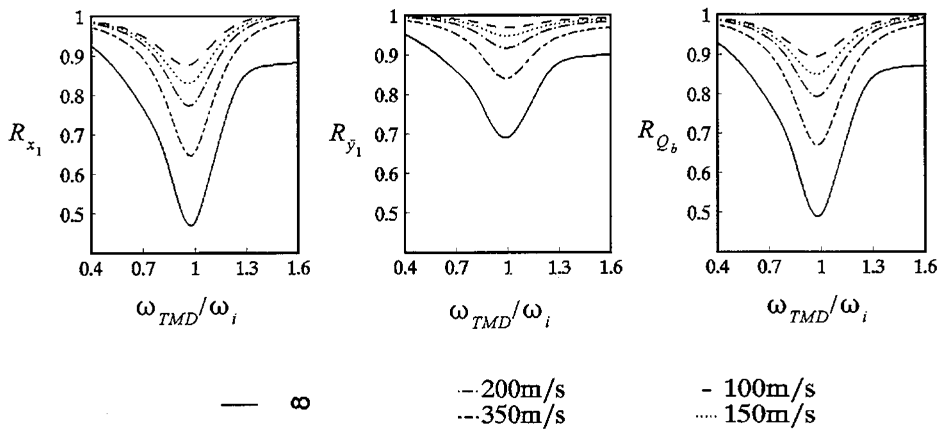

Figure 5. Responses of flexible-base structures: $\xi = 1\%$

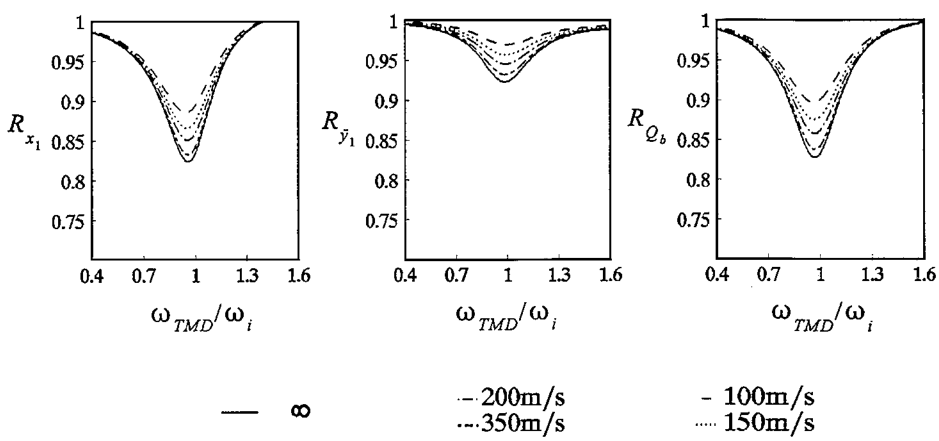

Figure 6. Responses of flexible-base structures: $\xi = 5\%$

base shear are mitigated by 10 per cent only. Similar conclusions can be drawn for moderately damped structures as demonstrated in Figure 6. However, the reductions in all interesting responses such as displacement, acceleration and base shear are much less. For example, the RMS displacement and base shear are reduced by 9–17 per cent only.

Comparisons between Figures 5 and 6 also indicate that the damper's performance is more sensitive to structural damping when a structure is supported on stiff soil rather than on soft soil. When the soil becomes very soft, e.g. $V_s = 100$ and 150 m/s, there is almost no change in the damper's effectiveness regardless of structural damping. This indicates the predominant effect of material and radiation damping from soil medium in those cases as implied in Table II.

Figure 7 shows the normalized translational and rocking displacements of the rigid footing when $V_s = 100$ and 150 m/s. It can be seen that for both $\xi = 1$ and 5 per cent, the tuned mass

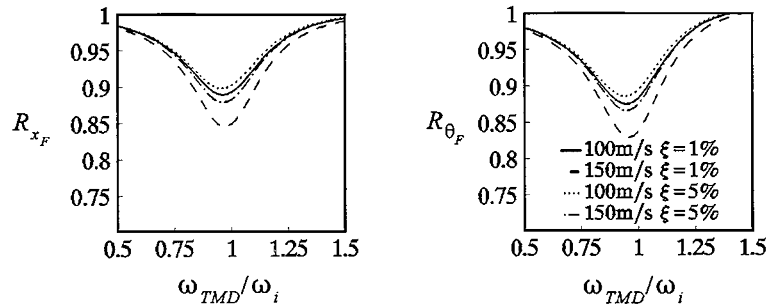

Figure 7. Responses at the rigid footing

damper has little difference in performance to suppress the base movement. This result is consistent with the conclusion drawn for structural responses.

Effects of soil–structure interaction on structural responses

To see the effect of soil–structure interaction on dynamic responses, an interaction factor is defined by

$$\alpha_\eta = \frac{\min \eta_s(\omega_{TMD}, \omega_s)}{\min \eta_i(\omega_{TMD}, \omega_i)} \tag{10}$$

for a structure controlled with an optimal tuned damper,

$$\alpha_\eta = \frac{\min \eta_s(\omega_{TMD}, \omega_s)}{\eta_i(\omega_s, \omega_i)} \tag{11}$$

for a structure controlled with a mistuned damper and

$$\alpha_\eta = \frac{\eta_s(0, \omega_s)}{\eta_i(0, \omega_i)} \tag{12}$$

for an uncontrolled structure.

In the equations above, $\eta_k(\omega_{TMD}, \omega_k)$ denotes a general quantity η of engineering interest for a fixed-base structure when $k = s$ and for a flexible-base structure when $k = i$. This is expressed as a function of the TMD's frequency and the fundamental frequency of the system under consideration. For example, $\eta_i(\omega_s, \omega_i)$ means the response η of a flexible-base structure controlled with a damper tuned into the fundamental frequency of the superstructure, i.e. $\omega_{TMD} = \omega_s$. The quantity min $\eta_k(\omega_{TMD}, \omega_k)$ represents the minimum response η when the TMD is appropriately tuned into ω_k as indicated in Figures 5 and 6. It can be easily seen that the closer to unity the interaction factor α_η, the weaker the soil–structure interaction. When $\alpha_\eta > 1$, soil–structure interaction will result in a reduction of the response η.

A TMD can suppress the response of lightly damped structure more significantly than that of moderately-damped structure. Therefore, only the interaction factors corresponding to 1% structural damping ratio are presented in Figure 8. The solid and dotted lines in this figure respectively show the interaction factors for a controlled and uncontrolled structure while the

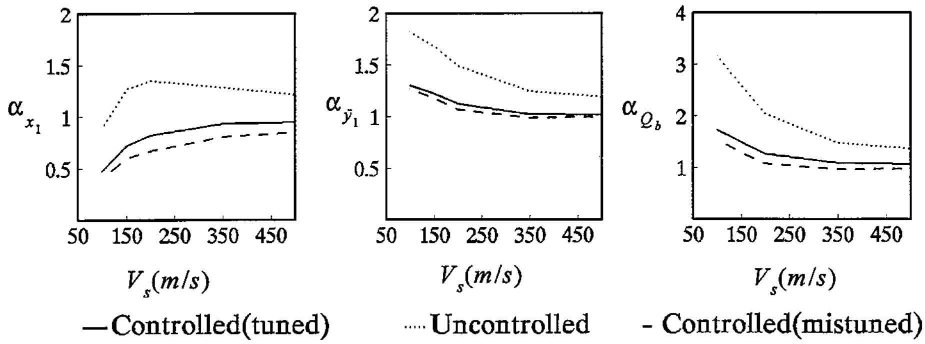

Figure 8. Interaction factors

dashed line for a structure controlled with a mistuned damper. It can be observed that the interaction factors, α_{x_1}, $\alpha_{\ddot{y}_1}$ and α_{Q_b}, of a controlled structure are always smaller than those of an uncontrolled structure and generally closer to unity for various shear wave velocities. This indicates the weaker soil–structure interaction due to the presence of dampers. The only exception for this rule is the total displacement of a structure resting on soft soil ($V_s = 100$ m/s), which probably results from the significant contribution of the rocking mode of footing vibration. Figure 8 also demonstrates that $\alpha_{\ddot{y}_1}$ and α_{Q_b} of a structure controlled with an optimally tuned or mistuned damper are greater than and asymptotically converge to unity as the soil material gets stiffer. Designing a structure and a damper without considering soil–structure interaction is therefore on the conservative side. It is also observed that all interaction factors are not particularly sensitive to mistuning of a damper for various shear wave velocities. This is because a soil mass of a small shear wave velocity dissipates more vibrating energy due to material and radiation damping and the dynamic responses of the supported structure are thus less sensitive to the frequency ratio $\omega_{\mathrm{TMD}}/\omega_i$ as shown in Figures 5 and 6.

DETERMINISTIC SEISMIC RESPONSE ANALYSIS

The root-mean-square response of a soil–structure–TMD system subjected to random loading, as discussed in the previous section, can give us information about the seismic effectiveness of the damper in a statistical sense. To understand the TMD's performance in a real earthquake event, however, deterministic analyses under a specific earthquake time history will shed more light. The NS component of the El Centro, California earthquake of 1940 is selected for this purpose. The first 20 s of the acceleration record is scaled down 0·2 g and then used as input for the following analyses.

Fixed-base structure

For a fixed-base structure, damping ratio is assigned as 1 and 5 per cent. The mass damper is tuned to 98 per cent the fundamental frequency of the structure. Figures 9 and 10 show a comparison between responses of the controlled (solid line) and uncontrolled (dotted line)

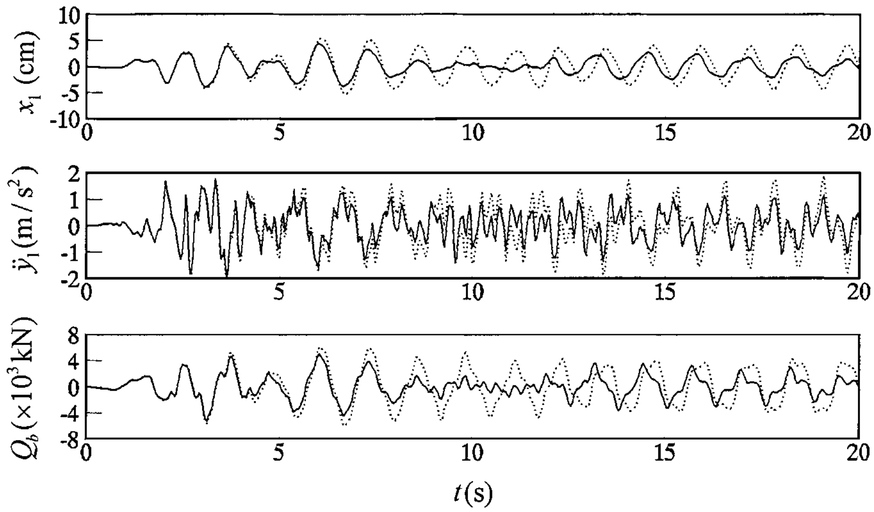

Figure 9. Response time histories of the fixed-base structures: $\xi = 1\%$

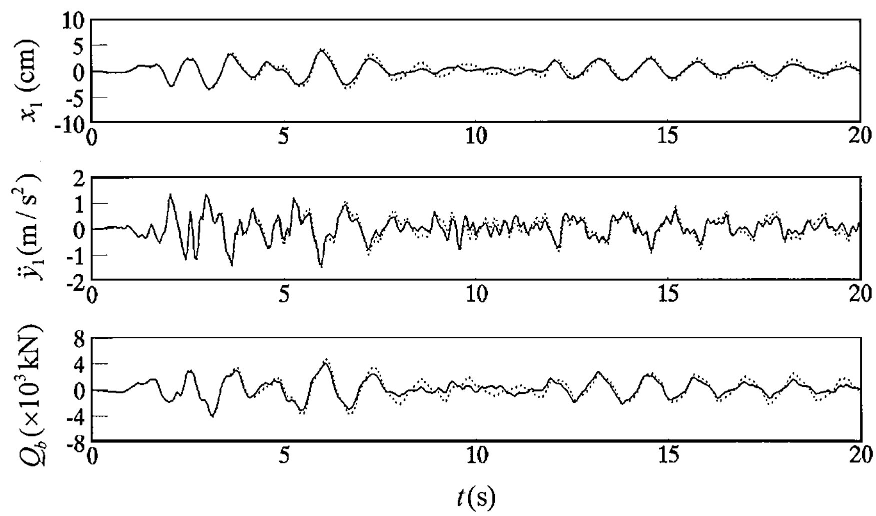

Figure 10. Response time histories of the fixed-base structures: $\xi = 5\%$

structure of 45 m high. As one can see from these figures, the tuned mass damper is effective in suppressing the responses of a structure of $\xi = 1$ per cent but far less so for $\xi = 5$ per cent.

Flexible-base structure

To see the maximum effect of soil–structure interaction on the TMD's performance, only one type of soil with shear wave velocity 100 m/s is considered. The damper is tuned to 98 per cent of

the fundamental frequency of the soil–structure system. The displacement, acceleration, and base shear of the controlled and uncontrolled structure are compared in Figures 11 and 12 for damping ratio $\xi = 1$ and 5 per cent, respectively.

Compared with the fixed-base structure, it can be seen that for $\xi = 1$ per cent, the tuned mass damper is much less effective in suppressing vibration. When $\xi = 5$ per cent, it becomes ineffective and sometimes even amplifies the structural responses slightly. These numerical results confirm the conclusions drawn from the stochastic analysis.

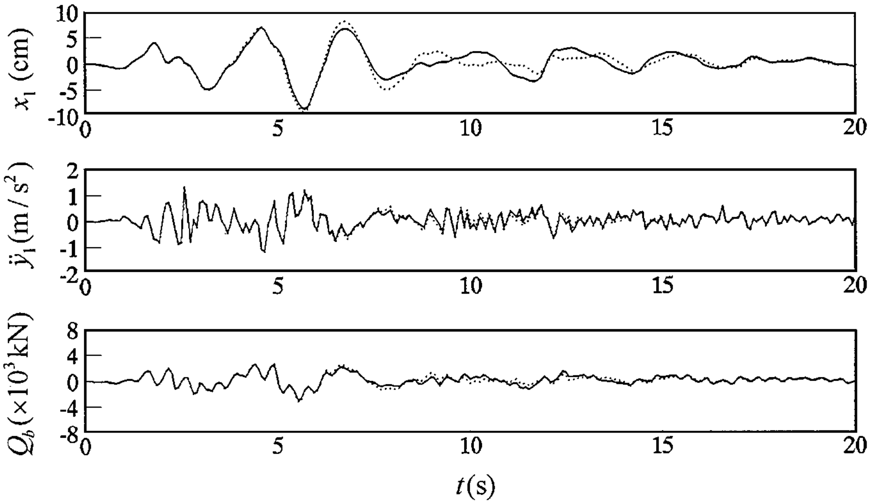

Figure 11. Response time histories of the flexible-base structures: $\xi = 1\%$

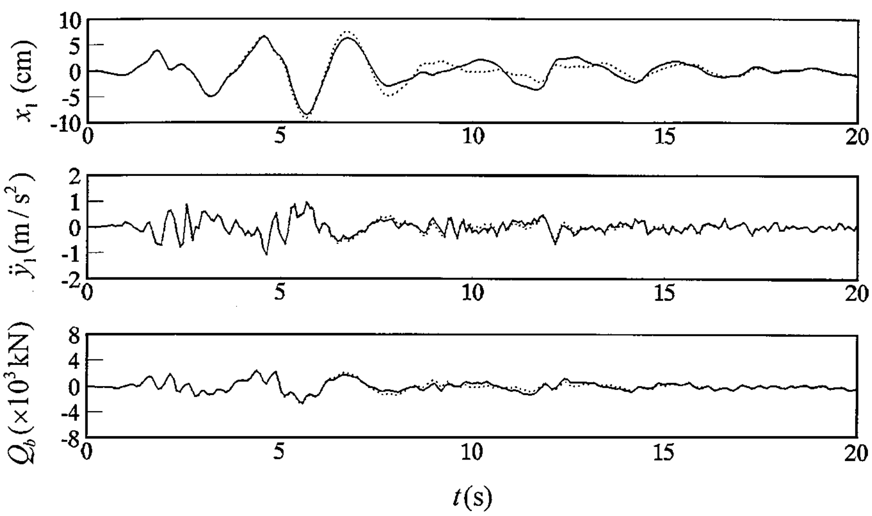

Figure 12. Response time histories of the flexible-base structures: $\xi = 5\%$

CONCLUDING REMARKS

Dynamic soil–structure interaction under earthquake loads is a complicated phenomenon. Unless the fundamental frequency of the structure is near that of its supporting soil strata, soil–structure interaction generally results in a reduction of the structural deformation and shear force at base. Assuming a fixed-base for a structure usually makes the structural design more conservative and therefore, is often acceptable for practical reasons. However, a tuned mass damper is required only when it can significantly reduce the structural responses. Understanding the actual performance of the damper system in an earthquake environment is thus pertinent for economic reasons.

Strong soil–structure interaction can greatly modify the damping characteristics of the structure, which in turn affects the performance of a damper system mounted on top of the structure. The damper's effectiveness rapidly decreases as the soil medium gets softer due to the significant contribution to the damping of the soil–structure system from soil material hysteresis and radiation effect. For structures resting on very soft soil, soil–structure interaction can make a damper on the structure totally ineffective. In order to reasonably evaluate the feasibility of using dampers to control the maximum structural responses, soil–structure interaction must be taken into account. In general, TMD is not a feasible choice for vibration control of the structures that are supported on shallow spread footings and underlying soft soil.

This study has focused on the TMD's seismic performance when it is mounted on structures of shallow foundations. In practice, pile foundations are often used for structures on soft soil with low bearing capacity. Further investigation on the dampers' effectiveness is necessary under these circumstances. In addition, the present study has considered a soil model of constant damping and compliancy. They are generally representative for small and moderate earthquakes. During large earthquakes, soil may behave nonlinearly and both damping and compliancy thus will vary with the intensity of the earthquake. This nonlinear effect on the TMD's performance should be studied in the future.

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